# Photo diode

# Prerequisite/Recapitulations

Knowledge of P and N type semiconductors

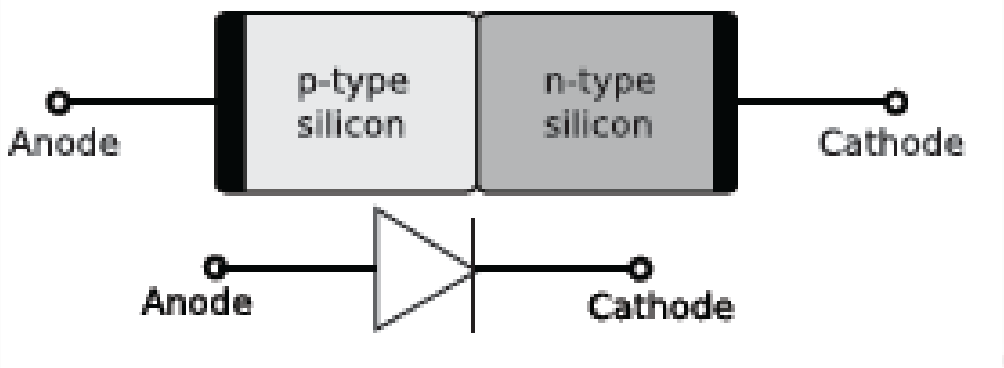
Knowledge of PN Junction diode

# Objectives

- Light absorption and emission
- The direct and indirect bandgap semiconductor
- Photodiodes

# Introduction

p-n junctions are an integral part of several optoelectronic devices. These include photodiodes, solar cells light emitting diodes (LEDs) and semiconductor lasers.

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# Light absorption and emission

A large number of optoelectronic devices consist of a *p*-type and *n*-type region, just like a regular p-n diode. The key difference is that there is an additional interaction between the electrons and holes in the semiconductor and light. This interaction is not restricted to optoelectronic devices. Regular diodes are also known to be light sensitive and in some cases also emit light. The key difference is that optoelectronic devices such as photodiodes, solar cells, LEDs and laser diodes are specifically designed to optimize the light absorption and emission, resulting in a high conversion efficiency.

Light absorption and emission in a semiconductor is known to be heavily dependent on the detailed band structure of the semiconductor. Direct bandgap semiconductors, i.e semiconductors for which the minimum of the conduction band occurs at the same wave vector, *k*, as the maximum of the valence band, have a stronger absorption of light as characterized by a larger absorption coefficient. They are also the favored semiconductors when fabricating light emitting devices. Indirect bandgap semiconductors, i.e. semiconductors for which the minimum of the conduction band does not occur at the same wave vector as the maximum of the valence band, are known to have a smaller absorption coefficient and are rarely used in light emitting devices.

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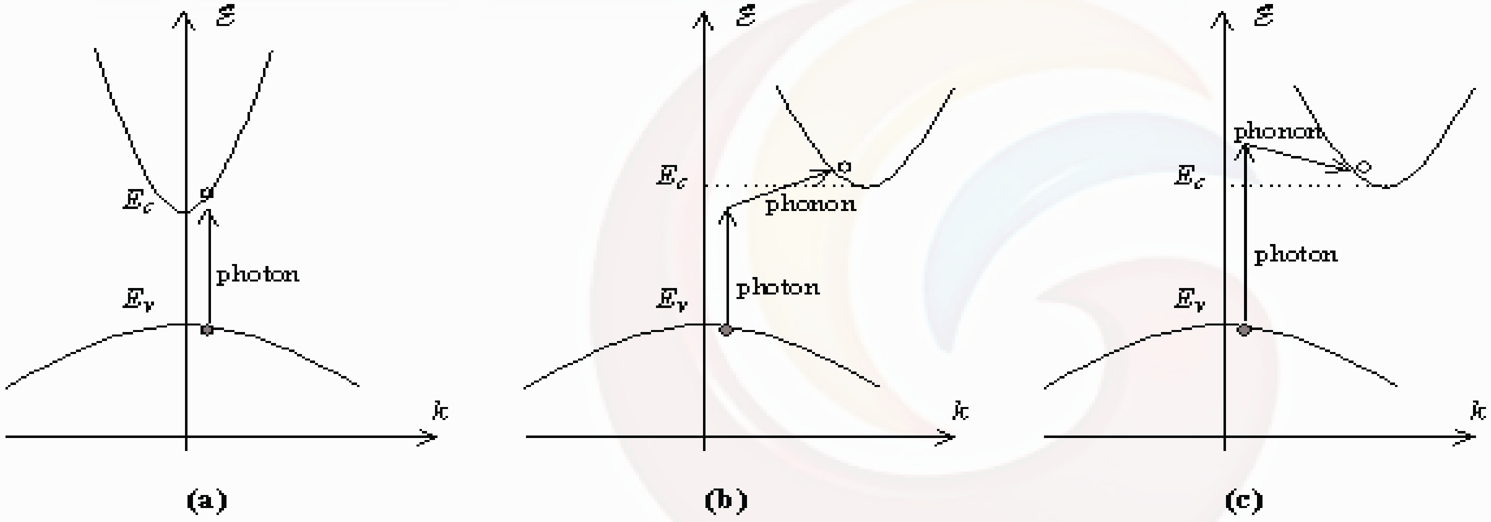
# Photon absorption




*E-k* diagram illustrating a) Photon absorption in a direct bandgap semiconductor b) Photon absorption in an indirect bandgap semiconductor assisted by phonon absorption and c) Photon absorption in an indirect bandgap semiconductor assisted by phonon emission.

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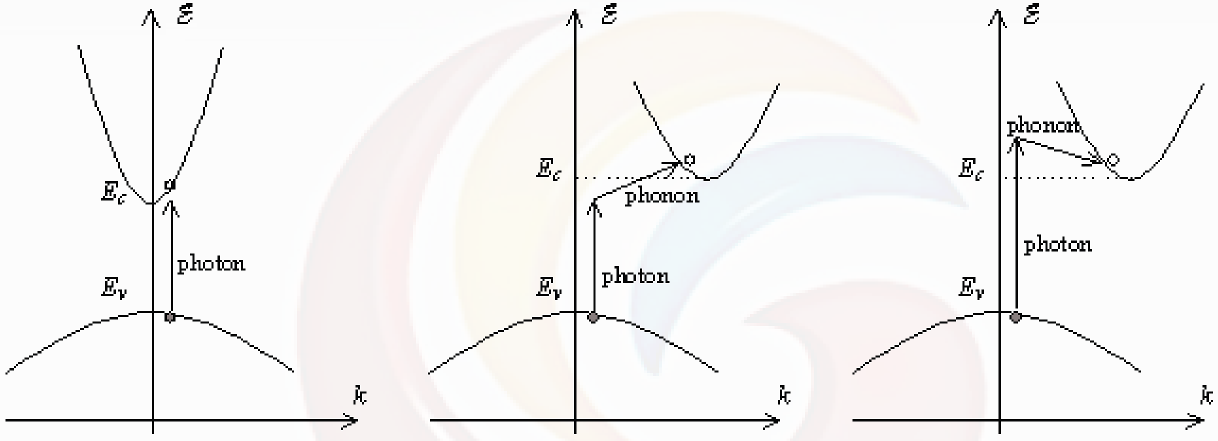
# The direct and indirect bandgap semiconductor




This striking difference is further illustrated with this Figure and can be explained based on the energy and momentum conservation required in the electron-photon interaction. The direct bandgap semiconductor, which has a vertically aligned conduction and valence band, is shown in Figure (a). Absorption of a photon is obtained if an empty state in the conduction band is available for which the energy and momentum equals that of an electron in the valence band plus that of the incident photon. Photons have little momentum relative of their energy since they travel at the speed of light. The electron therefore makes an almost vertical transition on the *E*-*k* diagram.

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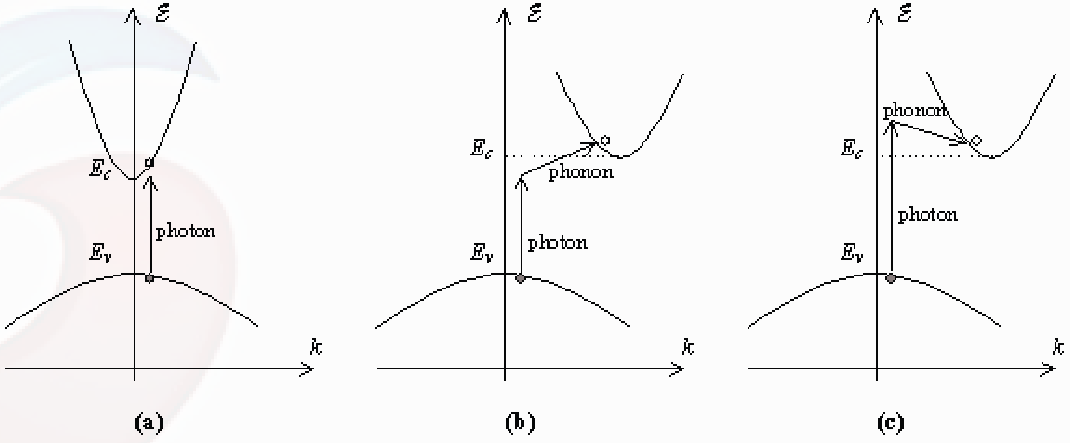
# The direct  and indirect bandgap semiconductor

For an indirect bandgap semiconductor, the conduction band is not vertically aligned to the valence band as shown in Figure (b). Therefore a simply interaction of an incident photon with an electron in the valence band will not provide the correct energy and momentum corresponding to that of an empty state in the conduction band. As a result absorption of light requires the help of another particle, namely a photon. Since a phonon, i.e a particle associated with lattice vibrations, has a relatively low velocity close to the speed of sound in the material, it has a small energy and large momentum compared to that of a photon. Conservation of both energy and momentum can therefore be obtained in the absorption process if a phonon is created or an existing phonon participates. The phonon assisted absorption processes are illustrated with Figure  (b) and (c). Figure  (b) illustrates the absorption of a photon aided by the simultaneous absorption of a phonon, while Figure  (c) depicts the absorption of a photon, which results in the emission of a phonon

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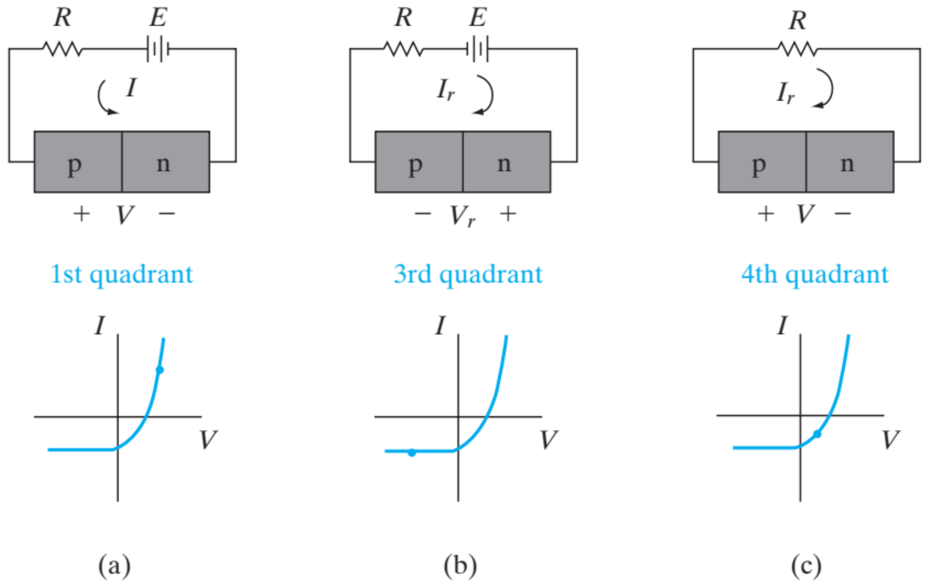
# The direct and indirect bandgap semiconductor

The minimum photon energy that can be absorbed is slightly below the bandgap energy in the case of phonon absorption and has to be slightly above the bandgap energy in the case of phonon emission. Since the absorption process in an indirect bandgap semiconductor involves a phonon in addition to the electron and photon, the probability of having an interaction take place involving all three particles will be lower than a simple electron-photon interaction in a direct bandgap semiconductor. As a result one finds that absorption is much stronger in a direct bandgap material. Similarly, in the case of light emission, a direct bandgap material is also more likely to emit a photon than an indirect bandgap material. While indirect bandgap materials are occasionally used for some LEDs, they result in a low conversion efficiency. Direct bandgap materials are used exclusively for semiconductor laser diodes.

# Photodiodes

When the photodiode is operated in the third quadrant of its *I–V* characteristic (Fig.b), the current is essentially independent of voltage but is proportional to the optical generation rate. Such a device provides a useful means of measuring illumination levels or of converting time-varying optical signals into electrical signals.




Operation of an illuminated junction in the various quadrants of its I–V characteristic; in (a) and (b), power is delivered to the device by the external circuit;
in (c) the device delivers power to the load.

# Photodiodes

Photodiodes and crystalline solar cells are essentially the same as the p-n diodes. However, the diode is exposed to light, which yields a photocurrent in addition to the diode current so that the total diode current is given by:

$$I = I_s\left(e^{V_a/V_t} - 1\right) - I_{ph}$$

where the additional photocurrent, $I_{ph}$, is due to photogeneration of electrons and holes

**Two-terminal devices designed to respond to photon absorption are called *photodiodes*.**


(a) Reverse-bias operation using standard symbol

(b) Typical Photodiodes

Photodiode symbol

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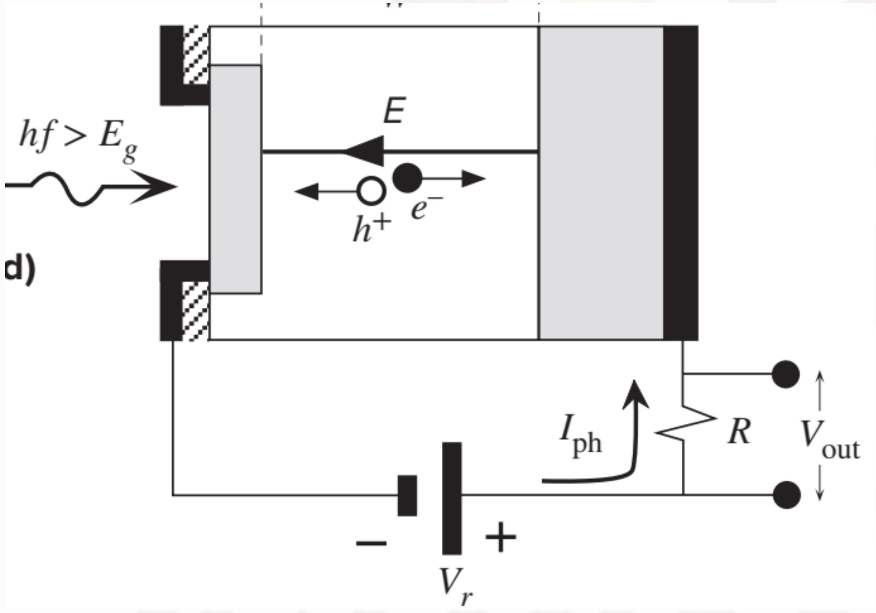
# Photodiodes

The additional photocurrent, $I_{ph}$, is due to photogeneration of electrons and holes shown in Figure  below. These electrons and holes are pulled into the region where they are majority carriers by the electric field in the depletion region.

Schematic representation of a p-i-n photodiode.




Motion of photo-generated carriers in a pin photodiode.

SO, it is desirable to dope at least one side of the junction lightly so that *W* can be made large. The appropriate width for *W* is chosen as a compromise between sensitivity and speed of response. If *W* is wide, most of the incident photons will be absorbed in the depletion region, leading to a high sensitivity. Also, a wide *W* results in a small junction capacitance, thereby reducing the *RC* time constant of the detector circuit.

# Photodiodes

In most optical detection applications the detector's speed of response, or bandwidth, is critical. For example, if the photodiode is to respond to a series of light pulses 1 ns apart, the photogenerated minority carriers must diffuse to the junction and be swept across to the other side in a time much less than 1 ns. The carrier diffusion step in this process is time consuming and should be eliminated if possible. Therefore, it is desirable that the width of the depletion region *W* be large enough so that most of the photons are absorbed within *W* rather than in the neutral p and n regions. When an EHP is created in the depletion region, the electric field sweeps the electron to the n side and the hole to the p side. Since this carrier drift occurs in a very short time, the response of the photodiode can be quite fast. When the carriers are generated primarily within the depletion layer *W*, the detector is called a *depletion layer photodiode*.

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$$C_{\mathrm{dep}} = \frac{\varepsilon_o \varepsilon_r A}{W}$$

# Photodiodes

The photo-generated carriers cause a photocurrent, which opposes the diode current under forward bias. Therefore, the diode can be used as a photodetector - using a reverse or even zero bias voltage - as the measured photocurrent is proportional to the incident light intensity.

The primary characteristics of a photodiode are the responsivity, the dark current and the bandwidth. The responsivity is the photocurrent divided by the incident optical power. The maximum photocurrent in a photodiode equals

$$I_{ph,max} = \frac{q}{h\nu} P_{in}$$

Where $P_{in}$ is the incident optical power. This maximum photocurrent occurs when each incoming photon creates one electron-hole pair, which contributes to the photocurrent. The maximum photocurrent in the presence of a reflection, *R* at the surface of the photodiode and an absorption over a thickness *d*, in a material with an absorption coefficient, a, is given by:

$$I_{ph} = (1-R)(1-e^{-\alpha d})\frac{qP_{in}}{h\nu}$$

# Photodiodes

This photocurrent is obtained by integrating the generation rate over the absorption region with thickness, *d*. The photocurrent is further reduced if photo-generated electron-hole pairs recombine within the photodiode instead of being swept into the regions where they are majority carriers.

The dark current is the current through the diode in the absence of light. This current is due to the ideal diode current, the generation/recombination of carriers in the depletion region and any surface leakage, which occurs in the diode. The dark current obviously limits the minimum power detected by the photodiode, since a photocurrent much smaller than the dark current would be hard to measure.

# Study Questions

How Optoelectronic Technology is useful in Everyday Life?
Describe the Light absorption and emission by electrons.
Explain clearly the Photodiodes.

# References


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